LOCATION IMPROVEMENTS IN EAST ASIA: TOMOGRAPHIC MODEL ANALYSIS AND UTILIZING PUBLIC DATA FOR GROUND TRUTH IDENTIFICATION

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ABSTRACT

We continue to collect seismic catalog data from various sources and search that data for possible information to improve regional location in East Asia. Data collection and search efforts have greatly increased the availability of ground truth (GT) events and improved our ability to create detailed tomographic models for the area.

We have developed several regional phase tomography models for East Asia (see Rowe et al., 2008, these Proceedings) that display significant reduction in travel time residuals over starting models. Further analyses of these models are required to assess how such models will affect location accuracy and methods. We will determine how the tomography models reduce the travel time residuals for various stations within East Asia and what residual patterns remain after modeling. This will indicate whether any further location improvement can be expected by adding travel time correction surfaces to relocation methods in the area.

GT is usually collected through analysis of seismic, infrasound and satellite data or through direct on-site access. GT for areas where information is limited or denied must be derived from alternative sources. We obtained accurate and precise locations of two chemical explosions detonated in December 2007 in northern China through analysis of public information from the Internet and Google Earth™. The GT location of a multishot, delay-fired explosion detonated on December 20, 2007, is at 39.0529° N and 106.1155° E with a precision of GT1 or better. We located the epicenter of the second single-shot, contained explosion detonated on December 12, 2007, local time at 40.2671° N and 115.6955° E with a precision of GT0.3 or better. From seismic data recorded 48 km away, we determined the origin time of this explosion to be December 11, 2007, 19:00:18.91 UTC.

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OBJECTIVES

We continue to research ways to improve location and detection in East Asia through the gathering of GT information and the development of geophysical models to more accurately predict regional travel times. GT information is vital to calibration efforts in East Asia, as well as other areas of interest, and provides data that benefits other monitoring research efforts. New geophysical models are being created to obtain more accurate regional travel times (e.g., see Rowe et al., 2008, these Proceedings, and Myers et al., 2008, these Proceedings). These travel time models will greatly benefit the location calibration effort, with correction surfaces further improving the location accuracy.

The acquisition of new GT information is always beneficial to calibration efforts in monitoring research. We show that utilizing publicly available information on the Internet and through tools such as Google Earth™ can allow determination of GT points down to the sub-GT1 level.

RESEARCH ACCOMPLISHED

Reduction in Regional Travel Times Using Geophysical Models

Various models for East Asia have been produced by the monitoring community, both for geophysical interpretation and for travel-time calculation. Among these are Pn and Sn models (e.g., Begnaud et al., 2008; Hearn et al., 2004; Pei et al., 2007; Phillips et al., 2007) and the Pn Seismic Location Baseline Model (SLBM) (see Myers et al., 2008, these Proceedings). While these models tend to improve the residual misfit in arrival data, no model fits the data perfectly.

When attempting to remove regional travel-time residual trends, two-dimensional (2D) travel-time correction surfaces are generally used. These surfaces tend to remove the effects of local crustal structure, etc. from one-dimensional (1D) velocity models. Correction surfaces can also be applied to higher dimensional velocity and/or travel-time models.

We performed Pn travel-time tomography for Eurasia/North Africa as part of the National Nuclear Security Administration (NNSA) multilab SLBM effort. This effort used the "Unified" model that was developed by Los Alamos, Lawrence Livermore, and Sandia National Laboratories. The Unified model was the starting point for a tomographic inversion that solved for upper mantle slowness and gradient, as well as a crustal slowness modifier (see Myers et al., 2008, these Proceedings, for a full description) (Figure 1).

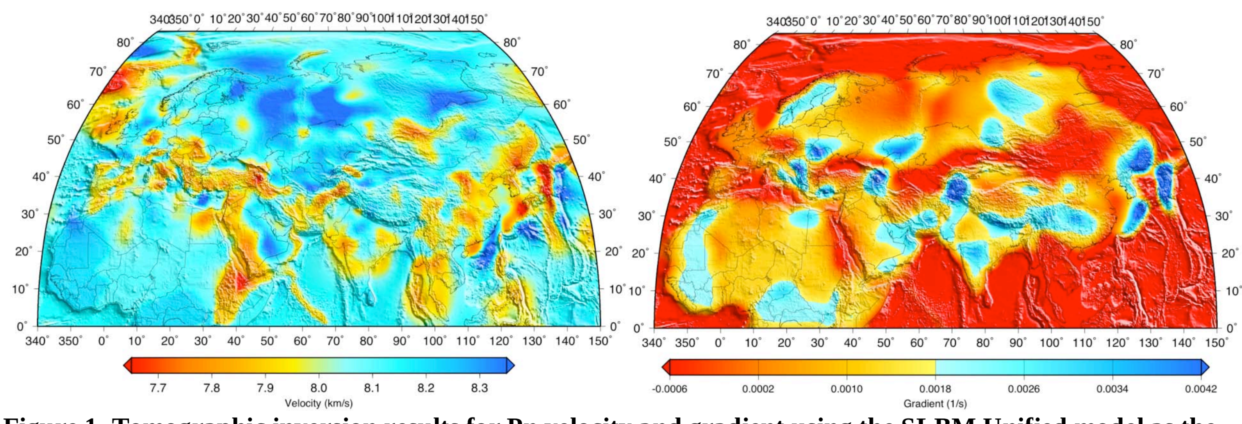

Figure 1. Tomographic inversion results for Pn velocity and gradient using the SLBM Unified model as the starting model.

For several stations in the western China region, we examined the resulting residuals when using the SLBM Pn tomographic model and a separate Sn tomographic model (Begnaud et al., 2008), looking for regional patterns and whether any such patterns were removed from the starting model by the tomographic inversion. For the Pn tomography (Figure 2), the stations all display highly variable residuals with little consistency in common areas. Using the SLBM tomographic model (Figure 1), residuals display more consistent values throughout the areas, with local and regional trends removed. Station WMQ has a variance reduction of 66% when using the tomography

model over the starting model. The Pn variogram for WMQ (Figure 3) before and after the inversion shows how the tomography stabilizes the residuals and reduces variability. The variogram for the starting model displays a possibly problematic correlation range (where the curve flattens out) while the variogram for the tomography is more realistic with an almost stationary curve.

After the inversion, residual patterns are still evident, though not as pronounced as in the starting model. Crustal velocity values were modified only with an overall modifier while crustal thicknesses (moho) were not varied at all. Any difference in the true crustal velocities or thicknesses could result in larger-scale residual patterns. In addition, the randomness of the resulting residuals after the inversion can be attributed to pick error. Travel-time corrections based on the tomography model are still warranted and should improve locations further than using the model alone.

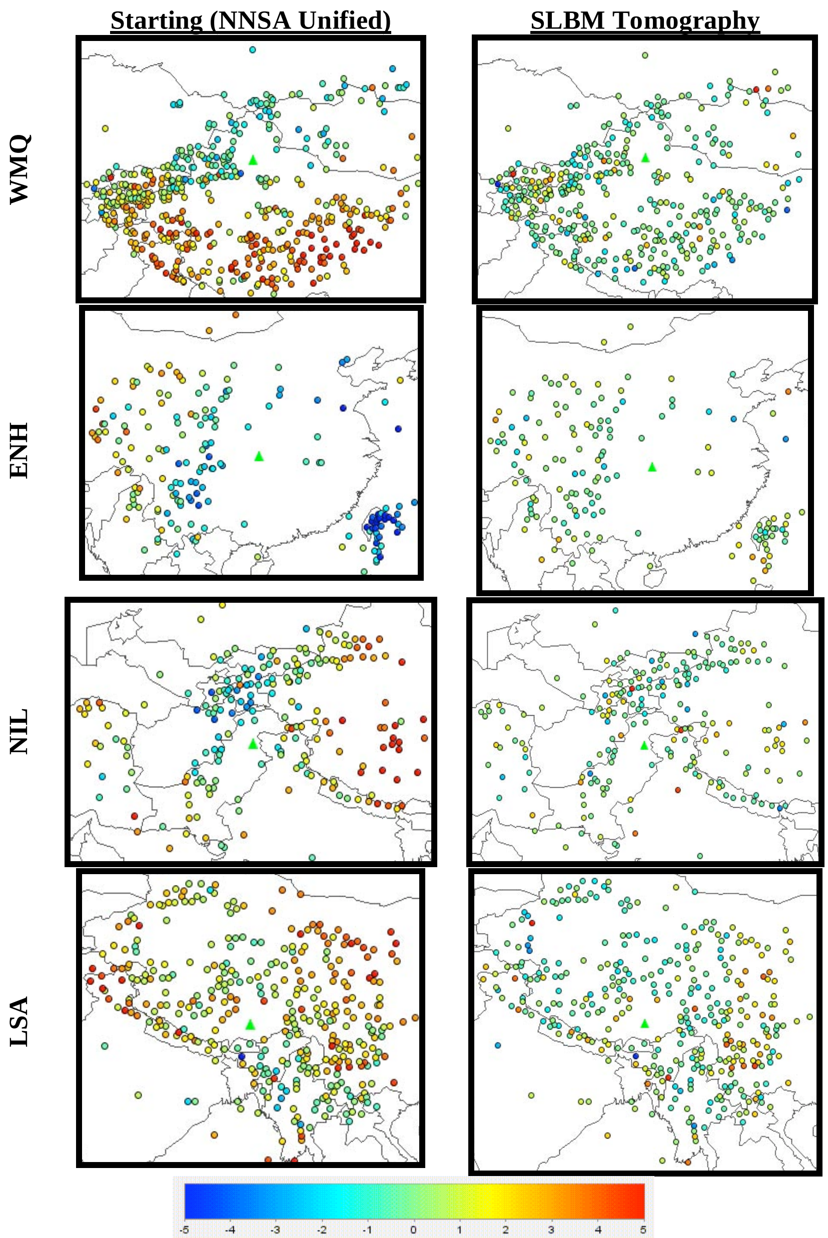

Figure 2. Pn residuals (s) using the starting and final SLBM tomographic models for four stations in western China. Residuals were clustered at 0.5 deg. All stations display areas with highly variable residuals when using the starting model, typically corresponding to tectonic regions. The SLBM tomographic model results in more consistent residuals.

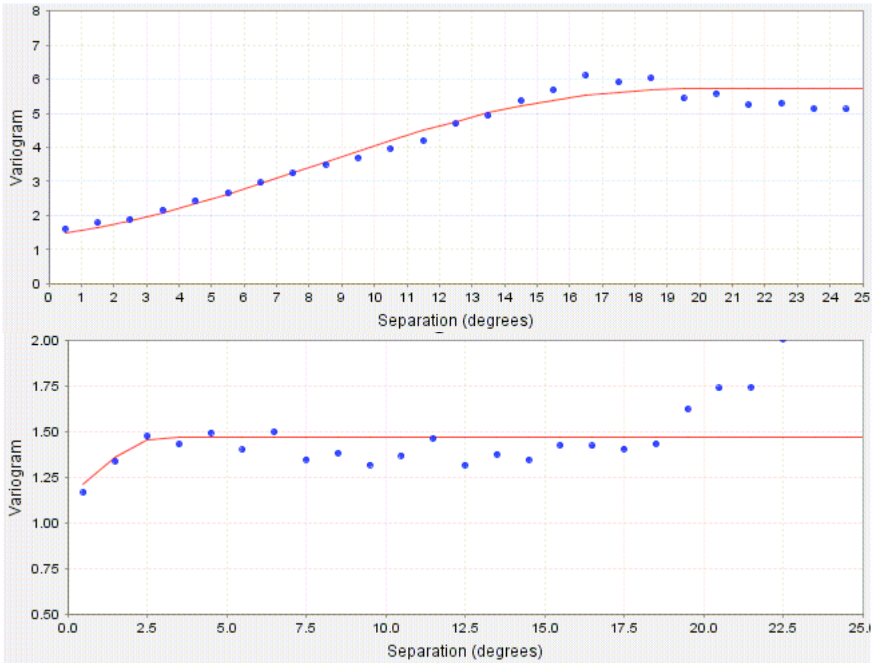

Figure 3. Pn variogram plots for station WMQ. (top) Starting model. (bottom) After tomography. The curve-fit for the starting model appears problematic with a higher correlation range (where the curve flattens out) than expected. The curve fit after the tomography displays more realistic values and is more stationary.

In addition to Pn models, we created an Sn tomographic model for Eurasia (Begnaud et al., 2008) (see Rowe et al., 2008, these Proceedings). The data for the Sn inversion had to be significantly culled as Sn is far more inconsistent than Pn for picking accuracy. Although the data for Sn are more variable than Pn, the tomographic model does remove the large biases observed in the Sn data (Figure 4). For station WMQ, the Sn variance was reduced by 53% and by 41% for station LSA.

The remaining Pn and Sn residuals after tomographic inversion still demonstrate the need for further 2D travel-time corrections. All stations display remaining residual patterns where the tomographic models need additional adjustment to match to observed travel times.

Ground-Truth Collection Through the Internet and Google Earth™

Accurate and precise GT information (time, location, size and type of seismic and infrasound events) is of vital importance to nuclear-explosion monitoring and the collection of new GT continues to be a major component of monitoring research (NNSA, 2004). GT is usually collected through analysis of seismic, infrasound and satellite data or through direct on-site access. GT can also be derived from alternative sources. Here, we demonstrate how we obtained accurate and precise GT (GT1 or better) from the Internet and Google Earth™ and the value of these resources in ground-truth collection especially in regions where information is limited or denied.

The GT that we collected concerns two chemical explosions detonated in northern China in 2007. One of the explosions is a multi-shot, delay-fired explosion designed to remove a mountaintop to expose the coal underneath. The other explosion is a single-shot explosion detonated as the source for a large-scale geophysical survey.

At the 2007 American Geophysical Union Fall Meeting, we learned that there would be a 5,000-ton, multishot, delayed-fired explosion on December 20, 2007, in northern China. On December 20, 2007, we started searching the Internet for information about this explosion using terms such as “China explosion.” Since the explosion was large enough, we obtained enough information including photographs of the mountain, where the explosion was conducted, and nearby buildings. Using this information, we were able to precisely locate the mountain and obtained the coordinate of the explosion at 39.0529° N and 106.1155° E with a precision of GT1 or better.

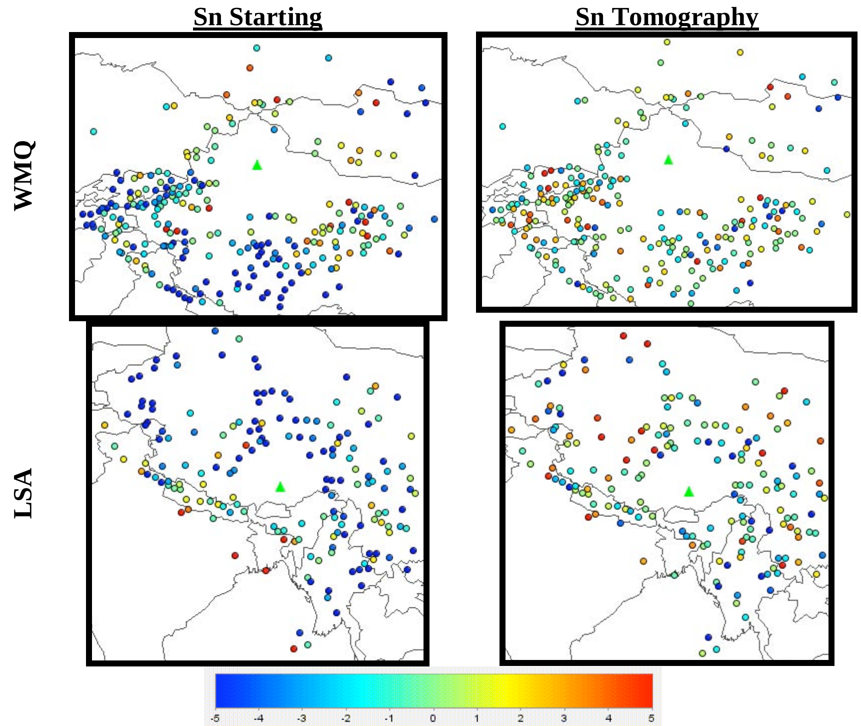

Figure 4. Sn residuals (s) using a starting (constant velocity/gradient) and final tomographic model. Shown are two stations in western China. Residuals clustered at 0.5 deg. Although the data are more variable than Pn, the tomography model does remove the large residual offsets observed.

When we searched the Internet about the December 20 explosion, we came across two news bulletins posted by the Anhui Seismological Bureau (ASB), a provincial bureau, and by the Institute of Geophysics, China Earthquake Administration (IGCEA) on their websites about another explosion conducted on December 12, 2007 (Dec122007). We will discuss in some detail in the following sections how we obtained precise GT location of this explosion.

Information Collection from the Internet

The ASB news bulletin, which was posted on November 27, 2007, mentioned that the anticipated explosion was part of a seismic experiment to be conducted at zero hours December 12, 2007, in Huailai region in northern China. The size of the detonation would be 50 tons of explosives. The bulletin posted by IGCEA provided more information about the experiment and the explosion. It stated that the experiment was designed to investigate, among others, the fine structure of the Earth's interior, regional travel time, strong ground motion, attenuation, coseismic electromagnetic effects, infrasound-seismic comparison and instrument calibration. No time, location or size of Dec122007 was disclosed in the IGCEA bulletin. Nevertheless, the bulletin included several photographs and figures related to the experiment. Figure 5 is a map of the experiment layout reproduced from IGCEA's bulletin. It shows the location of Dec122007, the locations of permanent and temporary seismic and infrasound stations and the regions where geomagnetic and strong-motion observations were made. From Figure 5, we estimated the location of Dec122007 to be at 40.2687° N and 115.6794° E. Since we do not know the error of the map, this location cannot serve as GT with confidence.

Based on the information from the two news bulletins about Dec122007, we decided to search the Internet again using refined terms such as "Huailai explosion." The search returned another news bulletin about Dec122007 posted on the website of the BIT Blast Ltd. (BIT Blast), the company that constructed and detonated Dec122007. More detailed information is revealed in this news bulletin. The bulletin stated that the location of Dec122007 was on a hill along a canyon near the village Longbaoshan in Huailai County of Hebei Province. In the surrounding area, there are orchards and a military explosive storage. According to the news bulletin, Dec122007 was detonated on December 12, 2007, at 03:00:20 local time (December 11, 2007, 19:00:20 UTC). The bulletin also confirms that the size of Dec122007 is 50 tons.

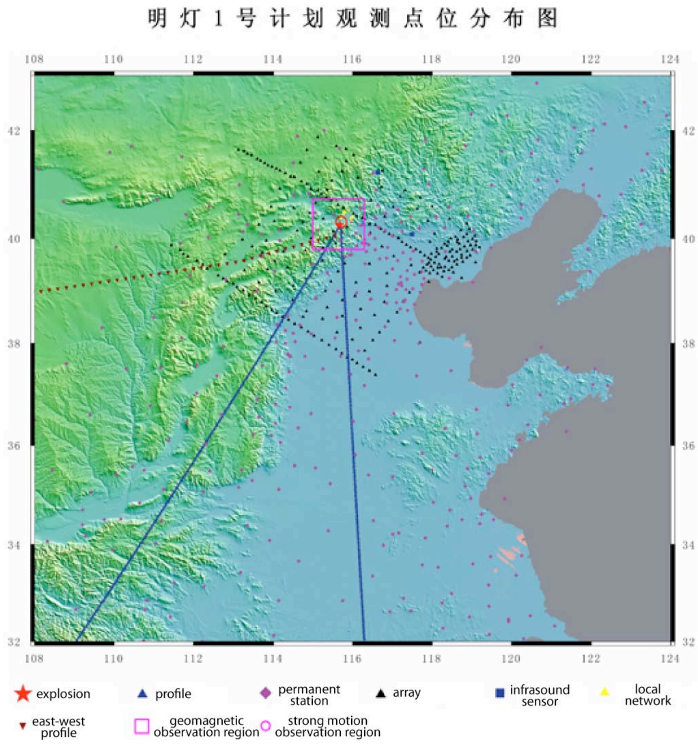

Figure 5. A map from IGEAC's news bulletin showing the location of Dec122007 and the layout of the geophysical survey. The original map legend has been translated into English.

Location Using Google Earth™

In addition to the text, the BIT Blast's news bulletin also includes several photographs of the test site. The photographs indicate that the company constructed Dec122007 by boring a horizontal tunnel on the side of a hill and excavating a chamber probably at the end of the tunnel for explosive emplacement. The photographs show the entrance to the tunnel and the road that leads up to the test site. The surface features near the test site revealed by the photographs make it possible for us to look for the exact location of Dec122007 in Google Earth™.

Google Earth™ is a virtual globe program that displays the Earth by superimposing satellite imagery, aerial photography, terrain data and maps (http://earth.google.com). According to Wikipedia (http://en.wikipedia.org/wiki/Google_Earth), for most parts of the world's continents, the spatial resolution of Google Earth™ images is 15 m or better. Most Google Earth™ images are one to three years old (http://earth.google.com).

We began our search for the test site in Google Earth™ by first locating Longbaoshan, the village mentioned in BIT Blast's news bulletin. Searching the Internet, we found a map of Huailai County, to which Longbaoshan belongs. Comparing the map with Google Earth™ images, we located the village in Google Earth™ (Figure 6).

Figure 7 shows another Google Earth™ image of Longbaoshan, this time looking south, along with the surrounding area. There are two canyons to the south of Longbaoshan and the Dec122007 test site could be in one of the canyons.

To locate the test site, we first estimated the orientation of the road that leads up to the test site so that we could look for road segments that have the similar orientation along the two canyons and branched-off roads in Google Earth™. Figure 8 is a photograph of the tunnel entrance from BIT Blast's news bulletin. From the shadows of different objects in the photograph, we estimated that the altitude of the Sun was about 24° and, with large uncertainty, the azimuth angle between the rock face above the entrance and the vertical plane containing the Sun was about 45° when the photograph was taken, assuming that the camera was properly leveled. The altitude and azimuth angles of

the Sun at a certain location and certain time can be found from various resources on the Internet (e.g., http://www.ga.gov.au/).

Using one of these tools, we calculated that at the Dec122007 test site and in late November to early December 2007, the Sun could have an altitude of about 24° at around 10:30 or 13:50. The azimuths of the Sun at these times are 155° and 206°, respectively. This means that the azimuth of the rock face shown in Figure 8 should be about 200° or 251°, again with large uncertainty. Figure 9 is another photograph from BIT Blast's news bulletin showing the road leading up to the tunnel entrance. The vertical rock fissure is visible in both Figure 8 and Figure 9. The road is at a steep angle with the rock face and appears to make a sharp left turn in front of the rock face. Taking into account the uncertainties in our estimates, we decided to investigate any road segments that are in the general west to northwest direction, and that make a left turn at the end of the segments. We identified a few road segments along the two canyons and in adjacent canyons that have the required characteristics. We then conducted detailed analysis comparing surface features shown in the photographs from BIT Blast's bulletin (Figure 9, Figure 10) with those in Google Earth™ images. Through laborious analysis and comparison, we identified the most likely location of the test site, which is marked by a red star in Figure 7.

Figure 6. Longbaoshan as is shown in Google Earth™. The village is adjacent to a sand dune, which is a tourist spot.

Figure 7. Google Earth™ image of Longbaoshan and the surrounding area. Possible locations of the orchards and the explosive storage are labeled. The likely location of Dec122007 is marked by a red star (see text for details.)

Figure 8. A photograph of the tunnel entrance from BIT Blast's news bulletin.

Figure 9. The road leading up to the tunnel entrance from BIT Blast's news bulletin. Numbers in the figure mark some of the surface features that are recognized in the Google Earth™ image (Figure 11).

Figure 11 is a Google Earth™ image of the probable test site looking in the northwest direction. Likely same surface features from previous figures are labeled with same numbers. Both the photograph shown in Figure 9 and the Google Earth™ image (Figure 11) were taken at times when the vegetation was green. The photograph shown in Figure 10 was taken in the winter when the vegetation became brown. Comparing the three figures, we found abundant similarities. The rock formation (1) has a patch of vegetation just to the right of the number "1" with similar shapes in all three figures. The rock face (3) has the same shape and a semicircular notch on the upper left (4) in all the figures. A piece of rock is seen inside the notch in all three figures as well. The rock face in Figure 11 has similar grass patches (5, 6) as those seen in Figure 9 and Figure 10. The horizontal extent of the rock face, estimated by analyzing the location of the green vehicle in Figure 10 relative to the rock face and the location of the photographer, is consistent with that measured in Google Earth™. A skinny tree (7) is seen in both Figure 9 and Figure 11. For some reason, the tree disappeared in Figure 10, possibly uprooted or broken by the explosion or the landslide afterwards.

In addition to the features marked by the numbers, there are other similarities as well. For example, Figure 9 shows that this segment of the road runs on the left side of the drainage. Figure 11 indicates the same configuration. There are also trees at same locations in different figures. The topography of the mountains in the background of the photographs is consistent with the topography in Google Earth™. We did not find apparent contradiction of features in the photographs and in the Google Earth™ image. The compelling evidence suggests that this location is likely the location of Dec122007.

Figure 10. A photograph of the Dec122007 test site after the explosion from BIT Blast's news bulletin. Minor landslides are seen on the side of the hill. Numbers in the figure mark some of the surface features that are recognized in the Google Earth™ image (Figure 11).

Figure 11. A Google Earth™ image of the likely Dec122007 test site. Numbers in the figure mark some of the surface features that can be seen in the photographs (Figure 9, Figure 10). The red star marks our location of Dec122007 using Google Earth™.

Since we have no information about the length of the tunnel and only a rough estimation of the tunnel direction from Figure 8, we placed the likely location of Dec122007 at the location of the hilltop with a coordinate of 40.2671° N and 115.6955° E that we read from Google Earth™. The location is marked in Figure 11. Using the Google Earth™ measuring tool, we measured distance between the explosion location and the tunnel entrance to be about 80 to 90 m. Since the horizontal extent of the hill is only about 300 m at most, the precision of the location should be much better than GT0.3. The location that we measured from the map in IGCEA's bulletin (Figure 5) is about 1.4 km to the west of the Google Earth™ location. Using seismic data recorded about 48-km away at BJT, we estimated the origin time of Dec122008 to be December 11, 2007, 19:00:18.91 UTC, 1.09 seconds earlier than that reported in the BIT Blast's news bulletin.

Measured from the Google Earth™ image, the azimuth of the rock face above the tunnel entrance is about 250°. Comparing it with our estimates from the altitude and azimuth of the Sun when the photograph shown in Figure 8 was taken, it appears that the photograph was taken at about 13:50. If it was the case, the time stamp in the photograph could be the correct time if we replace "AM" with "PM." The angle between the road leading up to the rock face and the rock face is about 60°, consistent with our assessment of a steep angle from the photographs

(Figure 9). The existence of orchards and a possible explosive storage in the surrounding area of the test site (Figure 7) is consistent with the description in BIT Blast's news bulletin.

CONCLUSIONS

Upper mantle tomographic models are being developed in East Asia for both Pn and Sn. The severe biases in starting models are generally resolved after the inversion, but residual patterns do remain and need to be accounted for in calibration procedures. Developing travel-time correction surfaces on top of these tomographic models will further improve seismic location efforts in East Asia.

Using the Internet and Google Earth™, we located two chemical explosions detonated in northern China in December 2007. The locations that we obtained can serve as GT1 or better for calibration purposes. The successful location of these explosions illustrates the possibility of using alternative means, in addition to the traditional seismic, satellite and direct-access methods, to obtain GT in regions where information is limited or denied.

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